PATTERNS OF AQUATIC INVASIONS IN UNITED STATES AND RELATIONSHIPS WITH KEY GEOGRAPHIC VARIABLES

By

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Abstract: Invasive species are a serious threat to biodiversity, and the increasing spread of invasive species due to human transport and environmental change is only escalating the issue. In aquatic systems, the effects of human-induced environmental changes within watersheds have not been quantified in relation to the populations of aquatic invasive species (AIS). Moreover, given the potential effects of increasing numbers of AIS on native species, it is important to estimate the degree of spatial coincidence between AIS and key geographic variables.

I performed a broad-scale spatial analysis of the distribution patterns of freshwater AIS of plants, vertebrates, and invertebrates for the contiguous United States to investigate distributional patterns and the density of AIS (number of invasive species per watershed area) in US watersheds, correlation of AIS diversity with geographic variables such as watershed distance to major ports of entry, dominant land cover, human population density, and mean nitrogen and phosphorus levels in watersheds, and to identify statically significant hotspots of invasion. I found that the density of AIS can be explained by distance to nearest port, human population density, percent open water, and the mean nitrogen level per watershed. Of the 2111 watersheds in this study, 64 watersheds were identified as statistically significant hotspots and 1351 watersheds were within 500 km of hotspots. These statistically significant hotspots, along with areas with a high number of AIS, should be evaluated for management purposes to help prevent further spread of AIS.

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CHAPTER I

INTRODUCTION

Biodiversity can be defined as the complexity of life on Earth manifested as ecological, taxonomic, genotypic and phenotypic diversity (Hooper et al., 2005; Wilsey et al., 2005). Loss or a decrease in biodiversity can severely affect the functioning of an ecosystem (Hooper et al., 2005; Loreau et al., 2001) by making it more susceptible to invasion and less stable when confronted with environmental fluctuations (Hooper et al., 2005; Peterson et al., 1998) due to shifts in food webs and niche partitioning. Ecosystem properties such as function and organismal distribution and abundance over time and space greatly depend on the biodiversity of an ecosystem (Hooper et al., 2005). These properties determine the goods and services the ecosystem provides to humanity (Hooper et al., 2005). Negative effects such as loss of diversity or functional changes may not be immediately noticeable but they can lead to ecological collapse (Peterson et al., 1998). Factors that can lead to a decrease in biodiversity include habitat degradation, pollution, nutrient loading, and invasive species, the later considered one of the main causes of biodiversity loss (Sala, 2000).

In aquatic systems, biodiversity loss is of concern in light of recent studies showing that ecosystems with higher species diversity more effectively reduce the nutrient load in water bodies (Cardinale, 2011; Cardinale et al., 2006;). Arguably, conservation of biodiversity could be promoted as a solution to the nutrient loading problem (Tilman et al., 1996; Scherer-Lorenzen et al., 2003; Reich et al., 2001; Hooper et al., 2005). However, ecosystems with high nutrient loadings usually experience reduction of biodiversity (Cardinale, 2011). A nutrient of global concern is nitrogen, since its input has more than doubled in the last decade through the use of fossil fuels and fertilizers, with the excess running off into waterways (Cardinale, 2011; Canfield et al., 2010). This run off increases eutrophication (Cardinale, 2011; Schindler, 1985) and acidification of water bodies (Schindler, 1985), which can lead to a decrease in biodiversity (Schindler, 1994; Vitousek et al., 1997a).

Another major threat to biodiversity and significant contributor to environmental change identified by policy makers and scientists is invasive species (Bax et al., 2003). In the continental United States alone over 2,100 invasive vascular plants species have been documented (Vitousek et al., 1997b). However, distributional trends have not been broadly investigated for aquatic invasive species (AIS). Most of the broad scale AIS studies have focused on fishes and have revealed negative effects of AIS on native species (Meador et al., 2003; McKinney, 2001; Stohlgren et al., 2006).

In this study I focus on AIS, known to disperse by various means, both natural (washed down stream, hitch hike on another organism, etc.) (Vander Zander et al., 2008) and human mediated (pet release, hobby boating, shipping, etc.) (Bax et al., 2003; Drake and Lodge, 2004; Hulme, 2009; Vitousek et al., 1997b). The human mediated invasions can be largely attributed to shipping and commerce (Hobbs et al., 2006). It is estimated that over 10,000 species are transported worldwide in ship ballast water alone (Carlton and Geller, 1993; Bax et al., 2003), and every 35-85 weeks a new species will establish at a major port (Bax et al., 2003). A study in Coos Bay, Oregon found 367 taxa originating in Japan in the ballast water of 156 ships (Carlton and Geller, 1993). Ballast water is one of the primary sources of invasion in coastal and marine environments (Drake & Lodge, 2004), due to the high numbers of species that can be found in ballast water at any given time (Carlton and Geller, 1993).

Human mediated dispersal of species is of concern because certain non-native species modify native habitats and these changes can increase the opportunities for other non-native species to invade (Simberloff, 1999). Moreover, some invaders can change the function of an ecosystem, by altering hydrology, decomposition, nutrient cycling, and disturbance regimes, causing the affected area to be altered for all species (Vitousek et al., 1997a).

The present study is a broad scale spatial analysis of the distribution of AIS in United States watersheds. The rationale for a broad scale analysis of AIS is to provide information for control and management efforts that require a regional context such as watershed proximity to areas with high numbers and density of AIS (hotspots), connectivity with ports of entry (Hobbs et al., 2006), and identification of watersheds that can become sources for further spread (Stohlgren et al., 2006; Holcombe et al., 2007; Ibáñez and Silander, 2009; McKinney, 2001). Dispersal is a natural, inherent trait of species, expressed, for example, through migration and searching for resources or mates. However, as the frequency and extent of movement of humans has increased, so has the transportation and introduction of invasive species. At both local and global scales, human activities can lead to an increase in number and abundance of non-native species and extinction of native species (Hooper et al., 2005; Vitousek et al., 1997a). Humans move species both deliberately and unknowingly (Vitousek et al., 1997a), and through ever-expanding transportation networks species can be spread around the world (McNeely, 2001). AIS represent the most species rich and diverse origins among invasive species (Cox, 1999).

My study included all exotic established freshwater AIS of plants, vertebrates, and invertebrates currently recorded in the United States Geological Survey Nonindigenous Aquatic Species database for the contiguous United States. I focused on the following three major themes:

1. Quantification of distributional patterns and the density of AIS in US watersheds.
2. Correlation of AIS diversity with geographic variables: watershed distance to major ports of entry, dominant land cover (percent crop, percent pasture, percent open water), human population density, and mean nitrogen and phosphorus levels in watersheds.
3. Identification of statistically significant hotspots of invasion

Methods

Aquatic Invasive Species Distribution and Density

The scale of the study was at USGS Hydrologic Unit Code 8 (HUC 8) because this was the finest scale that had the most information about presence of AIS, and the extent was the contiguous United States. Each HUC represents part of a drainage basin or a distinct hydrologic unit and the 2111 units at the scale of the contiguous United States form a standardized classification system of watersheds (Stohlgren et al., 2006). I compiled an initial AIS dataset of confirmed records of plants, invertebrates, and vertebrates through queries of the United States Geological Survey (USGS) Nonindigenous Aquatic Species Database (http://nas.er.usgs.gov/). Here I use the term invasive species synonymously with exotic species (Colautti and MacIsaac, 2004). Hence, I refer to species that do not occur naturally in the United States and that have been introduced most likely by humans, either accidentally or intentionally. This delineation is less problematic than that of species naturally occurring in the United States that have expanded their home ranges either naturally or mediated by human transport and/or modification of the environment. I further limited my queries to established species, thus avoiding accidental records or unsuccessful introductions (Appendix 1). Records with either missing locality information or incorrect locality information (e.g., mismatch between watershed HUC 8 and state) were checked using other search engines, museum records, and herbarium records (Appendix 2). The data compiled from USGS NAS and additional sources (Appendix 2) were filtered so that only one record per species in a HUC 8 unit was retained. All records were then imported in ArcGIS (ESRI) for visualization, summary statistics calculations by taxonomic group (plants, invertebrates, and vertebrates), and analysis of hotspots of invasion (Bertness et al., 2002) based on AIS density calculated as species richness of AIS per unit watershed area.

Geographic Variables and Multiple Regression Analysis

To investigate whether AIS density by watershed can be explained by landscape characteristics, I generated several geographic variables using available data compiled at the same scale of HUC 8 watersheds. One of the variables considered was nutrient loading caused by agriculture or industry. In a more nutrient rich environment, selection favors those species that are fast growing, therefore outcompeting more slow-growing organisms (Tilman, 1987; Aerts et al., 1990; Wedin and Tilman, 1993; MacGillivray et al., 1995). Growth rate is one life history trait that an invader can use to outcompete native species that have other reproductive strategies. I compiled nitrogen and phosphorus data available from the Environmental Protection Agency's STORET and USGS National Water Information System databases for the years 2000-2013. These databases were queried and data were downloaded using the HydroDesktop application (http://hydrodesktop.codeplex.com/). Records from both databases were averaged by watershed in ArcGIS. Agricultural run-off was estimated based on percent land cover type and crop type at the watershed level using the USGS National Landcover Database 2006 dataset (http://www.mrlc.gov/nlcd2006.php). The same dataset was used to calculate percent open water in each watershed. Percent of each landcover variable was calculated as the number of pixels per watershed area.

To estimate the importance of ports of entry for AIS density, ports included in the U.S. Department of Transportation Bureau of Transportation Statistics (2009), as well as the Great Lakes (Appendix 3), were considered for calculating watershed distance to ports. Distance was calculated by generating a vector grid with 10x10 km cells with the extent of the United States in Albers equal area projection to preserve true distances between any two points. This spatial resolution (10x10 km) was chosen assuming that most anglers and recreational boaters would travel at least this distance. Distance was calculated from each watershed cell centroid to each watershed cell centroid that has a major port of entry using the application Geospatial Modeling Environmental (GME; http://www.spatialecology.com/gme/). Calculations were restricted to watersheds within a radius of 500 km around each watershed with ports to avoid millions of possible combinations. This is a rather arbitrary distance, but I considered it a conservative estimation given inland vessel transportation. GME output provided minimum distance values for each watershed cell centroid to each cell centroid in watersheds with ports.

Human population density for each watershed (number of individuals/m^2) was calculated from county census data for the year 2000, the most recent dataset available, downloaded from US National Atlas (http://www.nationalatlas.gov/atlasftp.html). The population density for a watershed overlapping with multiple counties was calculated as the average population density of those counties. Given the lack of overlap of Great Lakes watersheds with counties, population density for these watersheds was calculated by averaging the density values of all counties bordering the watersheds. Also, two watersheds on the East Coast did not overlap with any counties, thus the same method was applied.

The possible relationships between the geographic variables generated and watershed AIS density were analyzed in SPSS. All variables, including percent open water, percent crop cover, percent pasture, distance to ports of entry, average nitrogen per watershed, average phosphorus per watershed, and human population density, were first tested for correlation using Spearman's rank correlation coefficient. For pairs of correlated variables ($r^2 > 0.5$), one was excluded from the dataset used to run the regression analysis. Human population density was excluded the relationship with AIS and ports has been heavily studied. A multiple regression analysis was used to test for significant effects of variables on density of AIS.

Identify Statistically Significant Hotspots of Invasion

AIS raw numbers and density were used separately to identify watersheds that represent statistically significant hotspots, that are watersheds that had high numbers of AIS or density values and were surrounded by watersheds with similarly high AIS numbers or density values. To identify hotspots I used the Getis-Ord analysis (Getis and Ord, 1992), implemented in ArcToolbox (ESRI), which tests the null hypothesis of random distribution. For each watershed and its neighbors, a local density sum is calculated and compared proportionally to the sum of all watersheds' number of species or density values. A statistically significant z score ($P \leq 0.05$) is obtained when the watershed local sum is different from the expected local sum and that difference is too large to be explained by random chance (i.e., random distribution of local sum values). After the hotspots were statistically identified, distance to the nearest hotspot was calculated only for AIS density hotspots (by applying the same methods as distance to nearest port; see above) to identify the watersheds within 500 km of an AIS density hotspot. These watersheds could experience higher rates of invasion due to the proximity to such AIS hotspots. The pattern of AIS hotspots based on raw numbers was similar to the distribution of AIS raw numbers, thus no distance calculations were performed.

Results

The contiguous US was represented by 2111 watersheds, of which 1825 had at least one AIS record. There were 286 watersheds without any AIS records, which may represent non-invaded watersheds or could reflect sampling basis (i.e., no or little sampling). The HUC 18050004 that includes the southern half of San Francisco Bay, parts of Alameda, Contra Costa, and Santa Clara counties in California had 96 AIS, the highest number of AIS in this study (Fig. 1A). The AIS records were also separated and mapped by taxonomic group: plants, vertebrates, and invertebrates. In the invertebrate taxonomic group, there were 1126 watersheds with no records, 985 with at least one record, and HUC 1805004 in California contained the highest number of species, 80 (Fig. 1B). This was the same watershed that had the highest number of AIS for all taxonomic groups combined. In the plant taxonomic group, 524 watersheds had no records and 1587 had at least one record. HUC 4140201 in New York had the highest number of AIS plant species (28, Fig. 1C) and included all of Seneca County and most of Wayne, Cayuga, Onondaga, Tompkins, Schuyler, Yates, and Ontario counties. Lastly, for vertebrates, there were 812 watersheds with no records, 1219 with at least one record, and HUC 3090202 in Florida had the highest number of AIS vertebrates, 42 species (Fig. 1D). This watershed includes the south-east part of Florida from St. Lucie County to Monroe Country.

Due to the lack of records in individual taxonomic groups that could represent incomplete knowledge about presence of invasive species, subsequent statistical analyses were run using all AIS instead of values separated by taxonomic group (Fig. 1A). This approach was assumed to minimize error due to no records that in reality could represent missing records. Using the watershed area and the number of AIS per HUC unit I calculated AIS density (mean = 21.33, SD = 43.14, range = 0-714), and the areas that had the highest number of AIS were those bordering the coasts, Florida, the Gulf of Mexico, along the Great Lakes, and along the Mississippi River (Fig. 2).

The mean phosphorus per watershed compiled from available resources produced estimates too low to be considered accurate: the highest amount of phosphorus any one watershed averaged was 8.0 μg/L(Smil, 2000). Thus, this variable was not considered in subsequent analyses. Of the five variables analyzed, density of human population was correlated with distance to the nearest port of entry (r^2 <-0.614, P <0.0001), so it was eliminated (Table 1). Multiple regression showed significant correlations between the density of AIS per watershed and four variables: distance to the nearest port, mean nitrogen per watershed, percent crop, percent open water, and human population density because it was correlated with ports of entry (Table 2). All residuals for each variable had an even distribution.

The hotspot analysis was carried out using the total number of AIS and the density of AIS, separately, and produced two different results. When using the number of AIS, the spatial clustering of hotspots obtained was similar to that of watersheds with the highest numbers of AIS (Fig. 3). However, the arrangement of hotspots differed between the two approaches (Fig. 4), as the calculation of AIS density per watershed areas (Fig. 2) corrects for watershed size. This eliminated the Great Lakes and other open water dominated watersheds in Louisiana and California as the main hotspots of AIS, and highlighted fewer hotspots, especially in Florida and along the Gulf of Mexico. Interestingly, one hotspot was identified in the Midwest, in Illinois, where the Ohio River connects to the Mississippi River. However, similar patterns between the two maps of AIS hotspots were present, generally around major ports on the east and west coasts. A total of 64 hotspots (using AIS density) were identified and 1351 watersheds were within 500km from watershed hotspots (Fig. 5).

Discussion

The first aim of the present study was to provide a large scale overview of distributional patterns of AIS by taxonomic group and overall density in watersheds in the contiguous United States. The USGS NAS database and other supplementary sources of information allowed investigation of distributional patterns and revealed differences in both data availability and patterns between plants, vertebrates, and invertebrates. Since the lack of records in some watersheds may be the result of sampling bias or low detection rates, I did not analyze distribution and density by taxa, but instead used all AIS recorded in each watershed. There were 452 established AIS in the contiguous United States. The most densely invaded watersheds were located along the coasts and adjacent to the Great Lakes, as well as along the Mississippi River.

Second, I explored possible correlations between AIS densities and selected geographic variables. Not surprisingly, human population density was correlated with proximity to major ports, and proximity to ports was found to be a significant variable when compared to the density of AIS. This supports many previous studies showing that ballast water and shipping have a great influence on the movement and establishment of AIS (Bax et al., 2003; Drake and Lodge, 2004; Carlton and Geller, 1993; Hobbs et al., 2006; Hulme, 2009; McNeely et al., 1995; Vitousek et al., 1997a). Other significant variables were percent open water, average amount of nitrogen in a watershed, and percent crop. Percent open water can be explained by providing space for AIS, with more open water area, or resources available. Also, with a more open water area, there is a greater chance that the watershed is used more often by boaters or for shipping. This can increase spread of AIS by hitchhiking on boats and equipment. The present study suggests that mean nitrogen effects the density of AIS, thus it is probably the most concerning pattern observed because invasive species decrease biodiversity. However, if an area has an existing high biodiversity, the expectation is that the concentrations of nutrient levels will be reduced (Cardinale, 2011). On the other hand, since the most abundant pollutant worldwide is nitrate (Carpenter et al., 1998; Dodds, 2006), this is a very serious issue. With the amount of nitrogen available in watersheds increasing through pollution, the use of fossil fuels, and farming practices such as feed lots and chicken farms, nitrogen loading could be another key driver of establishment of and subsequent efforts to control AIS. The significant effect of percent crop on the AIS density identified here is expected given the positive effect of mean nitrogen on AIS density and run off of fertilizers through rain and irrigation.

I also identified statistically significant hotspot of AIS invasions. These hotspots and connected areas may be of great importance in the control and management of AIS. The density hotspot analysis, in addition to hotspots calculated using raw numbers, provides complementary information of AIS spatial clustering that is important for management practices. Areas with high numbers of AIS such as the Great Lakes, Florida, East and West Coasts have been of concern largely due to association of these areas with an entry point for shipping, and therefore considered the point source for many subsequent inland invasions. So, these areas remain a high priority for management and prevention of AIS spread. However, it is important to also consider areas identified as statistically significant in terms of AIS density, as these areas could lead to increased chances of inland transportation by hitchhiking or other types of spillover into other watersheds. As previously suggested, priority should be placed on managing areas that represent points of entry for AIS and areas with high numbers of AIS (Stohlgren et al., 2006). Such information is vital for identifying regions at risk and preventing further spread of AIS.

The present study had several limitations. Sampling bias or lack of records was one issue. Even with use of additional sources to USGS NAS, it is likely that some watersheds may have AIS that were not reported in any of the sources used here. The watersheds without records could not be included in AIS density calculations, so they could not be used in the regression or the hotspot analysis. If AIS were accurately accounted for in all watersheds, a different picture of hotspots may have emerged, although it is likely that many of the patterns would have been the same because the correlations with ports of entry and human population density will keep most of the hotspots where they are. Additionally, although it would be informative consider in the analysis watersheds that have had exposure to AIS and subsequently showed resistance to establishment of AIS, such absence information is not available, thus my study included only presence records. Finally, the phosphorus data compiled from the EPA STORET and USGS NWIS databases were not reliable and were excluded from the analysis. This could also mean that there were discrepancies with nitrogen data as well. However, this is a limitation that is currently impossible to overcome at this scale, as the data sources used were the best available.

Future efforts are needed to address the incomplete sampling of locations for AIS. For example, rapid screening methods for AIS should be developed considering cost, time, and accuracy issues. Maintaining a web-based database where all this information is accessible and reportable should be a long term priority. Without complete and up to date knowledge of presence of AIS, it is difficult to understand the magnitude of the problem or to develop adequate methods of management. Researchers, land managers, and other stakeholders need access to an accurate and comprehensive database of AIS to advance research and management practices (Crall et al., 2006). By adding new records to existing data sources in a centralized database such as USGS NAS, stakeholders can obtain a more complete representation of location of AIS and can better inform management practices (Ricciardi and MacIsaac, 2000). The presence of an invader in an area can indicate a potential for spread of that species into neighboring areas (Ricciardi et al., 2013). Systems that are the most vulnerable to invasions are the most important in assessing invasion patterns (Stohlgren et al., 2006).

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APPENDIXES

APPENDIX A

FIGURES

Figure 1: Spatial patterns of aquatic invasive species in the contiguous United States: total number of species (A); number of invertebrate species (B); number of plant species (C); and number of vertebrate species (D).

Figure 2: Density of aquatic invasive species in the contiguous United States.

Figure 3: Hotspots calculated using number of aquatic invasive species.

Figure 4: Hotspots calculated using density of aquatic invasive species per watershed.

Figure 5: Distance to nearest AIS-density hotspot, calculated for watersheds within a 500 km radius.

Figure 1

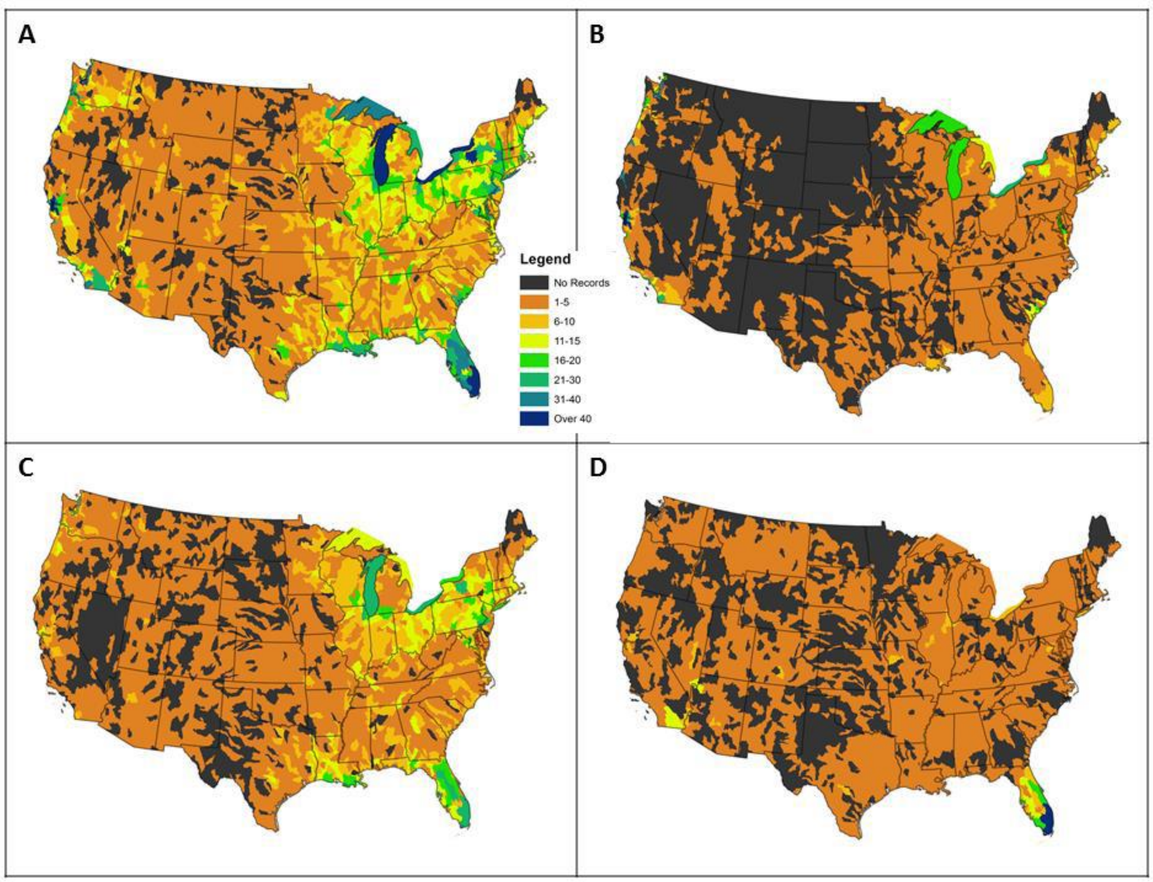


Figure 2

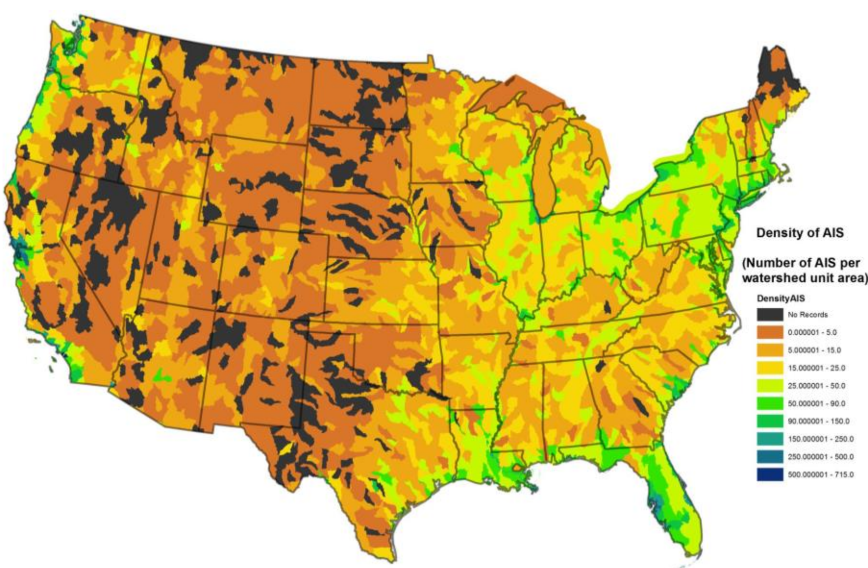
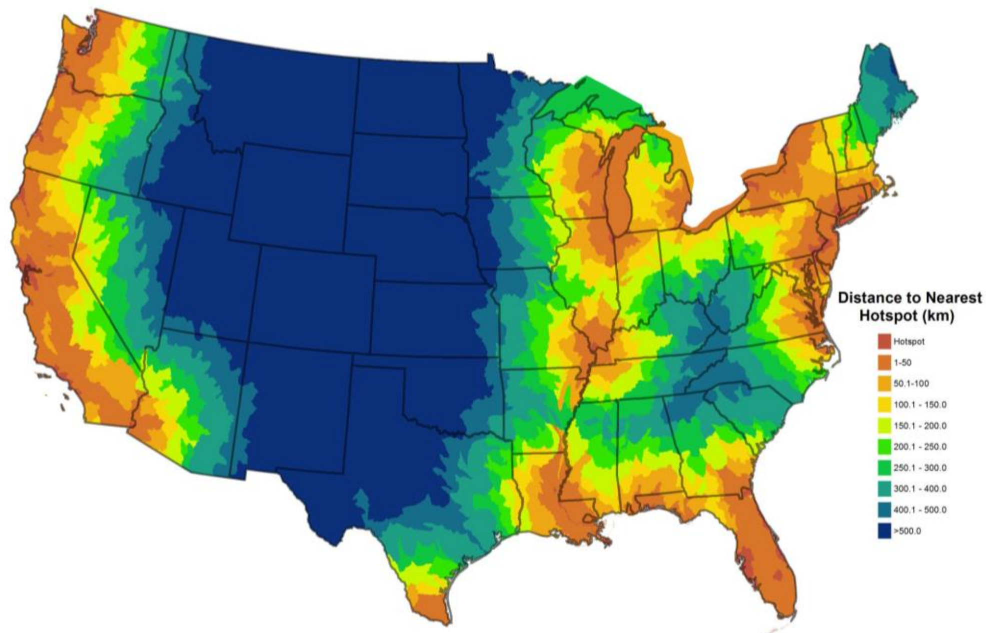


Figure 3

Figure 4

Figure 5:


Distance to Nearest Hotspot (km)
Hotspot
1-50
50.1-100
100.1 - 150.0
150.1 - 200.0
200.1 - 250.0
250.1 - 300.0
300.1 - 400.0
400.1 - 500.0
>500.0

APPENDIX B

TABLES

Table 1: Spearman correlation of geographic variables (the difference in N is due to available records).

		Mean Nitrogen	Percent Open Water	Percent Crop	Percent Pasture	Distance Nearest Port	Population Distance Per Square Miles
Mean Nitrogen	Correlation Coefficient	1	-0.012	0.407**	0.045	0.115**	0.108**
	Sig. (2-tailed)	<0.01	0.626	<0.01	0.058	<0.01	<0.01
	N	1742	1742	1742	1742	1742	1742
Percent Open Water	Correlation Coefficient	-0.012	1	0.204**	0.399**	-0.425**	0.459**
	Sig. (2-tailed)	0.626	<0.01	<0.01	<0.01	<0.01	<0.01
	N	1742	2111	2111	2111	2111	2111
Percent Crop	Correlation Coefficient	0.407**	0.204**	1	0.334**	-0.005	0.180**
	Sig. (2-tailed)	<0.01	<0.01	<0.01	<0.01	0.812	<0.01
	N	1742	2111	2111	2111	2111	2111
Percent Pasture	Correlation Coefficient	0.045	0.399**	0.334**	1	-0.274**	0.439**
	Sig. (2-tailed)	0.058	<0.01	<0.01	<0.01	<0.01	<0.01
	N	1742	2111	2111	2111	2111	2111
Distance Nearest Port	Correlation Coefficient	0.115**	-0.425**	-0.005	-.0274**	1	**-0.614****
	Sig. (2-tailed)	<0.01	<0.01	0.812	<0.01	<0.01	<0.01
	N	1742	2111	2111	2111	2111	2111
Population Distance Per Square Miles	Correlation Coefficient	0.108**	0.459**	0.180**	0.439**	**-0.614****	1
	Sig. (2-tailed)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	N	1742	2111	2111	2111	2111	2111

**. Correlation is significant at the 0.01 level (2-tailed).

Table 2: Multiple regression analysis using land cover information (percent open water, percent crop, percent pasture), proximity to ports, average nitrogen per watershed, and average phosphorus per watershed.

Geographic Variable	Coefficients	Significance
Land cover: Percent Open Water	0.126	<0.001
Land cover: Percent Crop	-0.064	0.008
Land cover: Percent Pasture	0.006	0.791
Distance to Nearest Port	-0.263	<0.001
Mean Nitrogen	0.106	<0.001

APPENDIX C

INVASIVE SPECIES BY STATE

1: The number of plant, vertebrate, and invertebrate aquatic invasive species by state for which records were available in the USGS NAS database, along with number of missing locations.

State Name	Number of Plant Species	Number of Vertebrate Species	Number of Invertebrate Species	All Aquatic Invasive Species	Missing Locality from USGS NAS
Alabama	25	11	9	45	3
Arizona	11	17	8	36	9
Arkansas	20	7	4	31	2
California	31	29	116	176	5
Colorado	8	9	6	23	2
Connecticut	21	5	10	36	4
Delaware	14	5	4	23	1
Florida	48	61	44	153	0
Georgia	22	8	5	35	2
Idaho	13	15	6	34	3
Illinois	36	13	15	64	11
Indiana	30	8	8	46	13
Iowa	10	5	3	18	3
Kansas	11	6	5	22	3
Kentucky	18	7	5	30	3
Louisiana	38	13	10	61	5
Maine	12	3	9	24	3
Maryland	20	7	20	47	4
Massachusetts	21	6	14	41	7

Michigan	45	7	28	80	3
Minnesota	28	7	23	58	13
Mississippi	24	8	8	40	6
Missouri	18	11	6	35	2
Montana	10	8	3	21	3
Nebraska	10	6	4	20	6
Nevada	5	19	5	29	1
New Hampshire	11	3	5	19	1
New Jersey	21	8	11	40	7
New Mexico	6	6	2	14	2
New York	53	13	42	108	14
North Carolina	23	9	11	43	3
North Dakota	7	4	1	12	3
Ohio	35	6	24	65	13
Oklahoma	13	7	4	12	3
Oregon	18	7	55	80	5
Pennsylvania	38	6	10	54	15
Rhode Island	12	4	9	25	4
South Carolina	23	4	24	51	3
South Dakota	9	7	2	18	3
Tennessee	20	7	3	30	2
Texas	28	22	14	64	7
Utah	8	5	5	18	3
Vermont	14	4	5	23	3
Virginia	23	7	16	45	2

Washington	24	8	62	94	3
Washington D.C.	7	3	1	11	0
West Virginia	11	5	4	20	3
Wisconsin	32	8	16	56	13
Wyoming	5	8	3	16	4

APPENDIX D

SOURCES

1: Sources of records used to complement and fill in the gaps in the USGA NAS database

Source Name	Website
Alabama Plant Atlas	http://www.floraofalabama.org/Specimen.aspx
Berkeley Mapper	http://berkeleymapper.berkeley.edu/
Calfora	http://www.calflora.org/
Consortium of Northeastern Herbaria (CNH)	http://neherbaria.org/CNH/collections/download/download.php
FishNet	http://www.fishnet2.net/search.aspx
Global Biodiversity Information Facility (GBIF)	http://www.gbif.org/
Invaders Database System	http://invader.dbs.umt.edu/queryplant1.asp
Kansas State University Herbarium of Vascular Plants	http://www.konza.ksu.edu:8080/SearchVascular/index.jsp
Louisiana State University Online Herbarium	http://data.cyberfloralouisiana.com/lsu/
Rocky Mountain Herbarium Database	http://www.rmh.uwyo.edu/index.php
Royal Botanic Garden Edinburgh	http://www.rbge.org.uk/databases
Southwest Environmental Information Network (SEINet)	http://swbiodiversity.org/seinet/collections/index.php
The Field Museum: Botany Collections Database	http://fieldmuseum.org/explore/department/botany/collections
The New York Botanical Garden	http://sciweb.nybg.org/Science2/vii2.asp
The Pennsylvania Flora Project of Morris Arboretum	http://www.paflora.org/
Thomas M. Pullen Herbarium	http://www.herbarium.olemiss.edu/searchmissnew.php
University of Maine Heraria	http://herbaria.umaine.edu/index.php?action=plants
Willard Sherman Turrell Herbarium	http://herbarium.muohio.edu/herbariummu/database.html

APPENDIX E

PORTS OF ENTRY

1: Ports of entry used for Spearman correlation and the multiple regression analysis and watershed distance to ports calculation.

State	Place
Alabama	Mobile
California	Long Beach
California	Los Angeles
California	Oakland
California	Redwood City
California	Richmond
California	San Francisco
California	Stockton
Florida	Jacksonville
Florida	Miami
Florida	Port Everglades
Florida	Tampa
Georgia	Savannah
Illinois	Great Lakes
Indiana	Great Lakes
Louisiana	Lake Charles
Louisiana	New Orleans
Maryland	Baltimore
Michigan	Great Lakes
Minnesota	Great Lakes
New York	Great Lakes
New York	New York
Ohio	Great Lakes
Oregon	Kalama
Oregon	Longview
Oregon	Portland
Oregon	Vancouver
Pennsylvania	Camden-Gloucester
Pennsylvania	Chester
Pennsylvania	Great Lakes
Pennsylvania	Marcus Hook
Pennsylvania	Paulsboro
Pennsylvania	Philadelphia
Pennsylvania	Wilmington
South Carolina	Charleston
Texas	Corpus Christi
Texas	Freeport

Texas	Houston
Texas	Port Arthur
Texas	Texas City
Virginia	Newport News
Virginia	Norfolk
Virginia	Richmond
Washington	Seattle
Washington	Tacoma
Wisconsin	Great Lakes

VITA

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Professional Memberships: Member, Zoology Graduate Student Society, Member, SACNAS – Advancing Hispanics/Chicanos & Native Americans in Science, Member, ASLO – Association for the Sciences of Limnology and Oceanography